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Effect of laser shock peening on bending fatigue performance of AISI 9310 steel spur gear

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A B S T R A C T

The effect of laser shock peening (LSP) on bending fatigue performance of AISI 9310 steel spur gear has been investigated in this study. To help to explain bending fatigue test results, residual stress distribution induced by LSP is studied by means of finite element modelling, results of which are verified by X-ray diffraction analysis. It is found that a compressive layer of desirable depth can be induced on the gear root fillet after LSP, and both magnitude and depth of compressive stress increase with laser energy. The bending fatigue test is conducted using the single-tooth bending method to compare fatigue performance of laser peened teeth and non-peened teeth, which is followed by relevant statistical analysis. S-N curves acquired from the fatigue test reveal that bending fatigue lives of gear teeth has been significantly improved after LSP in comparison with those non-peened teeth, and the bending fatigue limit is enhanced correspondingly. It is noticeable that higher laser energy does not necessarily lead to much better fatigue performance of test gears.

1. Introduction

As a common failure mode, fatigue exists as a great threat to many products. It happens without any warnings signs, and has caused significant loss to many fields [1]. Gear transmission in the aircraft is characterized by high speed ranging from 50 m/s to 100 m/s and considerable transmission power up to 1200 kw [2]. Gears are subjected to bending fatigue and fretting fatigue as well as resonance which is a serious problem in aeroengine. The unfavourable working environment can contribute to quick failures of the gears, which seriously undermine the reliability of aeroengine. A survey on gears failures in aeroengine indicates that bending fatigue is to blame for about 32% of the investigated gears failure [3]. To deliver high reliability of transmission gears, it is imperative to improve the bending fatigue life of gear teeth. Some surface processing techniques have been employed. They include shot peening [4], deep rolling [5] and low-plasticity burnishing [6], all of which can induce residual compressive stress on the surface and are flawed as well. Shot peening traditionally used for surface treatment has its limitation that the residual compressive stress is restricted in depth. The depth usually does not exceed 0.25 mm in soft metal [7]. Deep rolling may not be applicable to the edge or corner of the target metal.

Laser shock peening (LSP) is an effective surface processing technique with great advantages over other techniques [8]. It can induce desirable residual compressive stress which averagely exceeds 1 mm in depth and be applied on the complex geometries [7]. Target metal for LSP is generally coated by an ablating layer. Laser pulses of high energy and short width are used to irradiate the thin coating layer, which is subsequently vaporized into high-temperature high-pressure plasma, and the expanding plasma explodes to generate high-speed shock wave which will propagate into the target metal [9,10]. When peak pressure of the laser shock wave exceeds Hugoniot elastic limit of the target metal, laser peened area will be plastically deformed and expands outward. The expanding area is restricted by surrounding metal. Residual stress arises from the interaction of laser peened area and its surroundings. During LSP, target metal is subjected to pure mechanical treatment with a coating layer on it, and thermal effect on the metal behaviour can be neglected [7,11,12].

LSP has been reported to modify the microstructure of target alloy [11,13] and improve the mechanical properties including hardness and corrosion resistance of target steel [14]. In addition, it has been proved capable of improving the fatigue performance of stainless steel [15] and bulk metallic glass [16]. It has also been employed to extend fatigue life of the 7075 aluminium alloy [17,18], TC11 titanium alloy [19] and TC6 titanium alloy [20] for

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application to metallic aircraft components. However, most research targets on fatigue performance of specimens like dog-bone [21] and open-hole specimens [22]. Few studies investigate the influence of LSP on bending fatigue performance of gears, especially those high speed and heavy duty gears.

This work aims to investigate the effects of LSP on bending fatigue performance of AISI 9310 steel spur gears. Both the modelling and the experiment are included in this work. The modelling part mainly includes determination of pressure-time history, establishment of a constitutive model and solution. In the experimental part, the bending fatigue test is conducted with the aid of the single-tooth bending method, and its results are statistically processed to compare the bending fatigue life of laser peened teeth and non-peened teeth.

2. Materials and experiment

2.1. Description of the gear

AISI 9310 steel known for its superior hardenability can achieve high case hardness combined with high strength and toughness inside after proper heat treatment. It is used to fabricate transmission gears which make up the fundamental part of the transmission system in the aeroengine. Nominal chemical compositions of AISI 9310 steel are listed in Table 1. The AISI 9310 steel gears in this study are case carburized at 930 °C, quenched at 830 °C and then tempered at 200 °C. Subsequently the induced internal stress inside the gears is relieved at 180 °C. Gear teeth after heat treatment possesses case hardness of RC56 and core hardness of RC35. Dimensions of the investigated gear are given in Table 2. The tooth form is a 20° pressure angle involute profile with a nominal 0.01 mm radius edge break at the tips and sides of the teeth. Tooth fillet radius is 1.1 mm. To remove rust and stains on the tooth surface, the tooth root is grounded with 1200 grit sandpaper prior to ultrasonic cleaning of the whole gear.

2.2. Laser shock peening process

LSP is performed on the root fillet using a Nd:YAG laser system operating at a wavelength of 1064 nm, pulse duration of 16 ns and frequency of 2 Hz. The laser spot size is 3 mm in diameter, and laser pulse energy of 7 J and 9 J is used in this study. Corresponding laser power densities can be calculated with Eq. (1), and they are presented in Table 3.

$$I = \frac{Q_L}{A_L T_L} \tag{1}$$

where I is laser power density, Q_L is laser pulse energy, A_L is the laser spot size, and T_L is the laser pulse duration.

The laser beam passes through the confining layer of water and irradiates the ablating medium layer [23]. Commercially available dark tape is used as the ablating medium layer which can serve as an absorbent layer as well as protect the root surface from adversely thermal effects [24,25]. LSP is conducted at room temperature. Fig. 1 is the experimental process for LSP. The gear is clamped by a fixture as shown in the figure. Fig. 2 is the tracking path for LSP on gear root fillet. Overlapping ratio is 50%.

3. Finite element modelling and results

3.1. Pressure model

According to the study of Fabbro et al. [26], plasma pressure soars as soon as the laser is activated and drops slowly after laser is switched-off. A one-dimensional model is proposed further, which assumes that laser intensity is uniform on the laser peened area. Wave propagation in confining layer and target metal is treated one-dimensional in the model. It has been widely used in a lot of works and proved effective [12,27,28].

The model is adopted to predict temporal profile of plasma pressure in this study. During LSP, plasma arises from interaction between laser beam and coated metal. According to Fabbro's study [26], thickness and pressure of plasma are related as per Eq. (2).

$$\frac{dL(t)}{dt} = \frac{2}{Z}P(t) \tag{2}$$

where $L(t)$ is plasma thickness, $P(t)$ is plasma pressure, Z is effective impedance of the interface and t is a given instant. Z can be calculated with the following Eq. (3).

$$\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} \tag{3}$$

where Z_1 and Z_2 are impedance of confining layer and coating respectively.

In addition, relationship between laser power density $I(t)$ and plasma pressure $P(t)$ can be described by Eq. (4)

$$I(t) = P(t)\frac{dL}{dt} + \frac{3}{2\alpha}\frac{d}{dt}[P(t)L(t)] \tag{4}$$

where α is correction factor regarding ratio between plasma internal energy and thermal energy.

During subsequent cooling of the plasma, which is assumed to be adiabatic, the following equations can be acquired.

$$P(t) = P(S)\left(\frac{L(S)}{L(t)}\right)^{\gamma_0} \tag{5}$$

$$L(t) = L(S)\left(1 + \frac{\gamma_0 + 1}{S}(t - S)\right)^{1/(\gamma_0+1)} \tag{6}$$

where γ_0 is specific-heat ratio and S is laser switched-off time.

When laser energy is 7 J, laser pulse Gaussian profile can be determined with the given laser parameters, which is presented in Fig. 3. Corresponding plasma pressure profile can be obtained by solving Eqs. (2) (6) numerically with laser pulse profile as input. Fig. 4 is the plasma pressure profile.

Spatial distribution of plasma pressure is another issue when laser spot is comparatively large. Overlapping rate in our study is 50%. It can contribute to a comparatively uniform residual stress distribution on laser peened area [7,27,29]. Therefore, spatial distribution of plasma pressure can hardly affect final simulation results, and it is assumed to be uniform on the laser peened area.

3.2. Constitutive model

During LSP, the target metal is subjected to high strain rate exceeding $10^6\ s^{-1}$. In the condition of such high strain rate, materials may experience strain rate hardening as well as thermal soft-

Table 1
Nominal chemical compositions of AISI 9310 steel.

Element	Carbon	Nickel	Chromium	Copper	Molybdenum	Manganese	Silicon	Sulphur
Weight%	0.11	3.24	1.23	0.12	0.12	0.63	0.26	0.005